Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2829-7895

Advancements in CNC Machining: Rectangular Boss Feature Validation and Toolpath Precision using STEP AP242 and B-Rep Data Structure

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ARTICLE INFO

Article history:
Received 3 October 2023
Received in revised form 5 December 2023
Accepted 23 December 2023
Available online 21 January 2024

Keywords:
CNC Milling Machine, STEP File, GDE approach, PMI Data

ABSTRACT

In the context of a CNC machining application, this study proposes an alternate approach for creating toolpaths designed explicitly for machining rectangular bosses utilizing the STEP AP242 file format as a data source. The suggested methodology ensures data accuracy and integrity maintenance by extracting exact geometric information from digital models using Geometric Data Extraction (GDE) tools. The value of the Cartesian multi-point decimal point in the data structure and variations in the reference number of the Cartesian point every time a user accesses and converts to a STEP (AP203) file are two drawbacks of AP203 when compared to the widely utilized AP203 in prior technique studies. This method makes it possible to create G-code efficiently, which is necessary for managing computer numerical control (CNC) machines, by utilizing the power of STEP AP242 and GDE. The process entails finding and separating the rectangular island milling features in the STEP AP242 files, taking out critical geometric characteristics, and creating toolpaths that are optimal for CNC machining. Through this approach, the final G-code instructions are guaranteed to be precisely calibrated to consider every island feature's distinct quality while preserving overall machining efficiency. Several real-world case studies and valuable applications are investigated to confirm the efficacy of the suggested method. The results show significant increases in productivity, decreased waste material, and improved precision of CNC machining, all of which contribute to a more effective and economical production process.

1. Introduction

ISO introduced STEP as an international standard to exchange product data between computer-aided design (CAD) systems [1]. ISO 10303-21 (Part 21), commonly referred to as Part 21, is a set of ISO 10303 standards that defines a universal format for representing product and process data using ASCII text files for exchange [2]. This standard has become widely adopted across industries and organizations [3]. Product data can then be exchanged among various CAD systems and computer-

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https://doi.org/10.37934/aram.113.1.176188

aided manufacturing (CAM) or engineering (CAE) software [4]. ISO 10303-21 facilitates the exchange of diverse product and process data, such as geometric information, metadata, and manufacturing specifications, such as tolerances and material properties. It also enables the inclusion of Product and Manufacturing Information (PMI), allowing the storage and exchange of non-geometric information such as annotations and dimension tolerances alongside geometries.

Previous studies have been conducted on feature recognition based on data in STEP, including linear shape features [5], circular [3], and the combination of features [5-8]. A cylinder with a blind hole using a drilling machine [9] and combining linear and circular features [4]. However, these studies are focused solely on the practical system for identifying the complete profile within the STEP file and converting it into G-code format without utilizing the STEP file type (AP242). Additionally, these studies do not demonstrate the ability to visualize the cutting tool's location for each profile. AP242 is a standard for data exchange, meaning it can transfer cutting tool data between different systems. Other formats may not be as widely supported, making it difficult to exchange data [10,11]. A complete search of the works of literature revealed that none of the studies had been done to identify the profile of the features such as a pocket, island, blind hole, etc., except the study from Haziq *et al.,* [12]. They identified profiles of geometric machining features for rectangular fillet blind pockets using the Geometric Data Extraction (GDE) approach. Given this gap in existing research, this study was motivated to conduct a study on identifying specific profiles for island features.

This paper presents an alternative methodology for generating toolpaths tailored to the machining of rectangle bosses using the STEP AP242 file format in the context of a CNC machining application as a data source. The proposed methodology involves identifying and isolating rectangular island milling features within the STEP AP242 files, extracting key geometric parameters, and generating optimized toolpaths for CNC machining operations. This approach requires creating a 3D CAD model of an island in CAD software and saving it in STEP file format (AP242). This file format integrates geometric dimensions and tolerances specified in AP203 and AP214 standards [13] and [14], with a GDE approach used to detect and extract desired island feature profiles accurately. STEP files in text format provide some general information regarding the 3D features of a model, such as Cartesian Points, Cylindrical Surfaces, Planes, Vectors and Directions. In this study, three island profile samples were examined separately, with each island having a different workpiece size in the same place. The accuracy of the results obtained from the proposed methodology will be verified through manual drawing and Math3D analysis.

2. Proposed Methodology

The proposed methodology involves identifying and isolating milling features with the rectangular boss found in the STEP AP242 data file. It includes extracting the main geometric parameters and subsequently generating toolpaths for CNC machining operations. The resulting G-code instructions are finely tuned to accommodate the various features of the rectangular boss while maintaining overall machining efficiency.

As shown in Figure 1, the design of the rectangular Boss was initially carried out in CAM software, namely SolidWorks 2022. The painting data will be converted into the STEP AP242 format. This data format will be studied using faces, loops, edges, vertices, and face direction. Subsequently, the geometrical database will be compiled, and Geometric Data Extraction (GDE) will be generated for the Rectangular Boss. The properties algorithm will be implemented based on the Plane Surface and line to determine the shape of the rectangular Boss data. In these cases, Cartesian Points play an important role. Dimensional information, such as length, width, and height, is extracted by referencing the Cartesian Point in STEP AP242. The maximum and minimum values for Cartesian

Points will be extracted to generate the Rectangular Boss Form. The feature recognition table for Rectangular Boss and the imaginary toolpath were produced, as shown in Table 2 and Table 4.

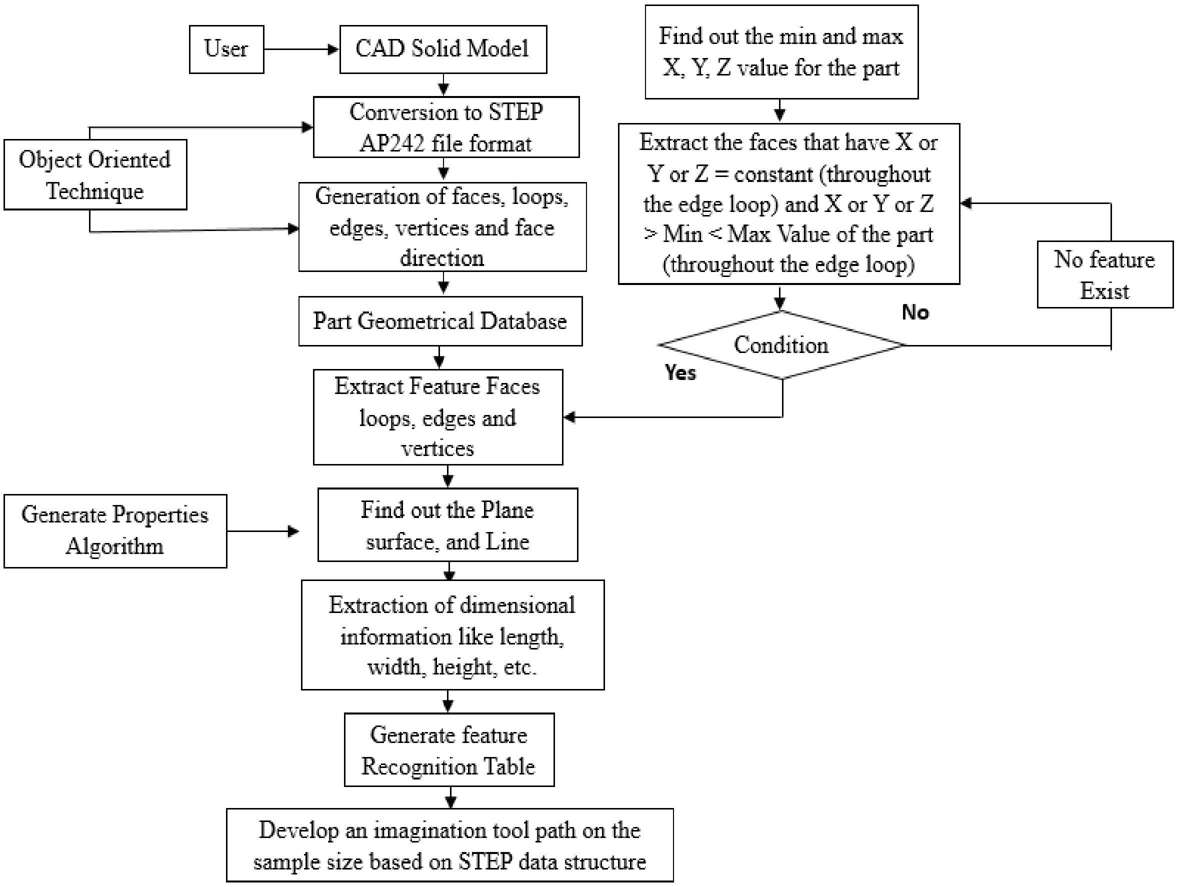


Fig. 1. Proposed method

Three milling samples were prepared and tested on rectangles with various diameters to validate the proposed approach. The results encompass an analysis of the data structure obtained from the STEP file, depicted in Figure 2, along with a description related to STEP, as detailed in Table 1. The GDE algorithm will be employed to classify the existing geometric data.

As shown in Table 1, CLOSED SHELL is the first step in identifying the relevant geometric data for machining the rectangular island feature in the STEP AP242 file. In the rectangular boss sample, the "ADVANCE_FACE" count remains consistent at 11. This "ADVANCE_FACE" element is in the "CLOSED_SHELL" structure. In the "ADVANCE_FACE" structure, two main components are found: "FACE_BOUND" and "PLANE." "FACE_BOUND", in turn, contains an "EDGE_LOOP" element within which "ORIENTED_EDGE" is located. "ORIENTED_EDGE" includes "EDGE_CURVE", which is the primary focus. Inside "EDGE_CURVE," there are three reference lines. Two lines represent the "VERTEX_POINT" element, while the third represents "LINE." "VERTEX_POINT" contains essential information, including specific X, Y and Z coordinate values. Meanwhile, "LINE" includes both "CARTESIAN_POINT" and "VECTOR." "VECTOR" is particularly important because it carries vector values and direction information for the X, Y and Z axes, indicating whether they are oriented in a positive or negative direction. Furthermore, the "PLANE" component contains "AXIS2_PLACEMENT_3D." This substructure has three reference lines representing "CARTESIAN_POINT" and two "DIRECTION" elements. This detailed information is extracted from the AP242 STEP file and forms the basis for generating G-code instructions for machining operations.

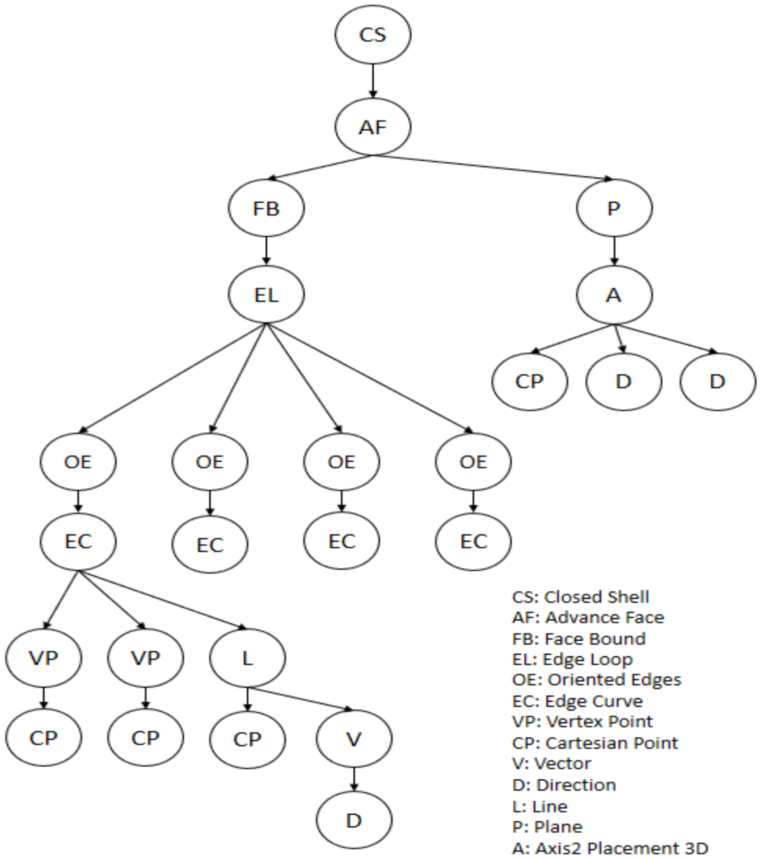


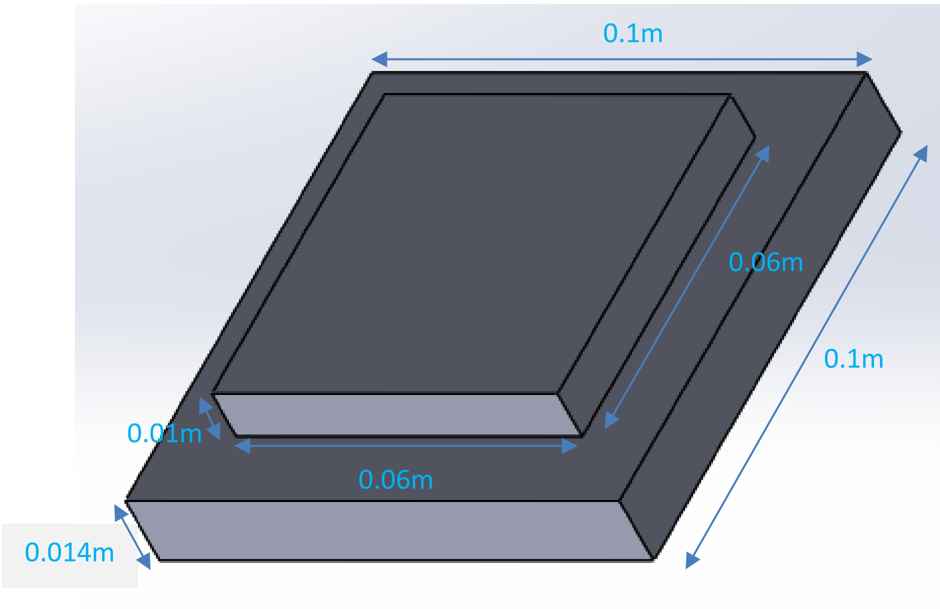
Fig. 2. Structure of STEP AP242 file for rectangular boss

Table 1
The description of the STEP file element

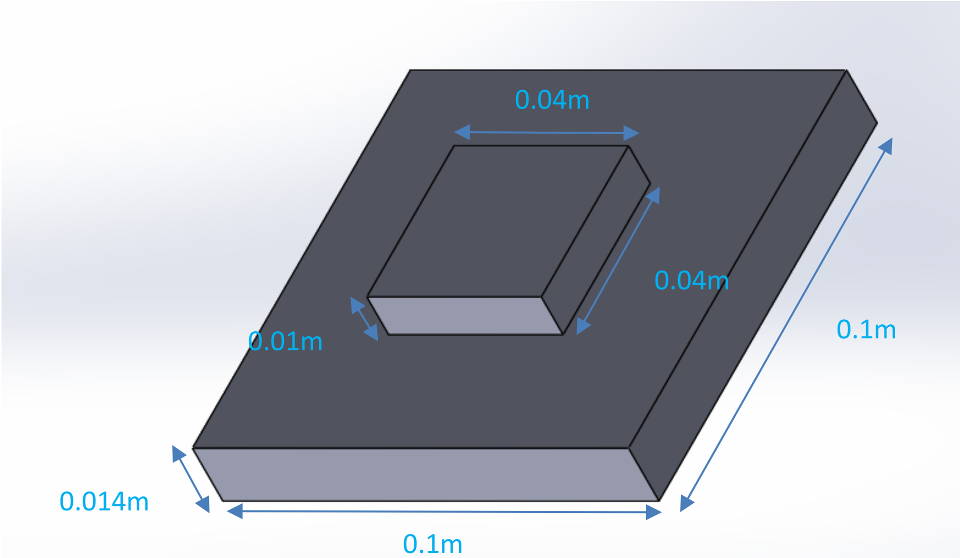
STEP Element	Description
CLOSED_SHELL	Is a closed solid object consisting of a set of surface entities linked to form a 3D object or solid enclosed by ADVANCE_FACEs.
ADVANCE_FACE	Each ADVANCE_FACE contains geometric information FACE_BOUNDs, FACE_OUTER_BOUNDs, and surface type (whether the surface is plane, cone, toroid, cylinder, or sphere).
FACE_BOUND	Is an internally tied side loop that covers the model's pocket or hole (The loop used to fasten the face)
FACE_OUTER_BOUND	Is an edge loop that covers the outer limit of the surface.
EDGE_LOOP	Is a complete set of edges that enclose loops
ORIENTED_EDGE	Contains data that describes the edge of a curve
EDGE_CURVE	Serves as storage of geometric information about the vertices and spatial coordinates that each cover the edge. Additionally, this geometric data consists of information such as lines and circles that describe the EDGE_CURVE type. The lines that make up the EDGE_CURVE are described as several sets of two Cartesian points and vectors that indicate the direction. In addition, the circle that makes up EDGE_CURVE is described as a set of multiple two Cartesian points, vectors showing the direction, radius, and center point of the circle.
VERTEX_POINT	A point defining the geometry of a vertex
CARTESIAN_POINT	Location of a point in Cartesian space
CYLINDRICAL_ SURFACE	Geometry is defined by surfaces, boundaries, and associated vertices.
CIRCLE	A cylindrical face where the geometry is defined by associated surfaces, boundaries, and vertices.
PLANE	Geometry is characterized by the associated surface, boundary, and vertices.
LINE	Line segments lie with Cartesian Points plotted on the line.

Figure 3 illustrates three samples created with the CAD application SolidWorks 2022. Each sample shares uniform dimensions: 0.1m in width, 0.1m in length, and a height of 0.024m. All blocks are consistently cut to a depth of 0.01m, indicating a standard z-axis depth of 0.01m. The coordinates extraction for X, Y, and Z values is accomplished using CARTESIAN_POINT. These coordinates are instrumental in determining the precise location, shape, and size of the geometric entity represented by the rectangular boss. Accuracy is verified by examining the maximum and minimum values for X, Y, and Z. Subsequently, Math3D software is employed for validation purposes. This entails the representation of X, Y, and Z values as points manually connected and plotted along the X, Y, and Z axes. This process creates a 3D drawing, subject to measurement and comparison with the original 3D SolidWorks drawing model. This meticulous approach ensures the precision of the extracted geometric data from the CAD model and allows for thorough verification. Then, the geometric data that has been extracted will undergo a further process to be used for the generation of tool paths in the form of ISO 16983 (Gcode), and this Gcode can be used in CNC machining applications. This tool path has been implemented using Gcode obtained from a manual calculation using a tool path size of 0.01m.

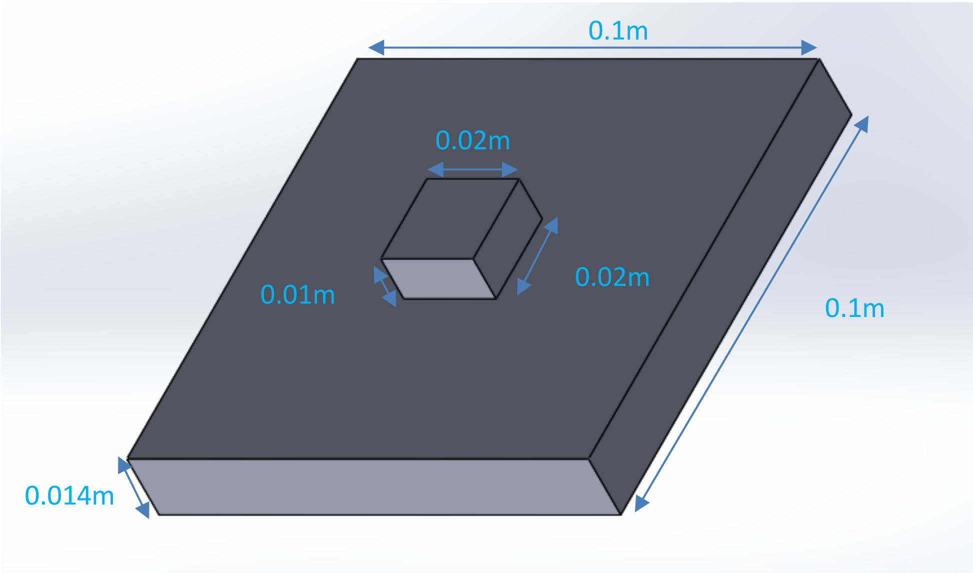
In conclusion, the proposed methodology uses a STEP AP242 data file to recognize and isolate rectangular boss milling parts, extract critical geometry characteristics, and provide precisely calibrated G-code toolpaths for CNC machining. Three milling samples with various rectangular dimensions were created and evaluated to verify this method. With "ADVANCE_FACE" constantly totaling 11 for rectangular bosses, the procedure includes the initial identification of "CLOSED_SHELL" as a vital step in isolating pertinent geometric data. This layered structure is made up of parts with names like "FACE_BOUND," "PLANE," "EDGE_LOOP," "ORIENTED_EDGE," and "EDGE_CURVE," each of which contains essential coordinates and directional data. The geometric data were precisely extracted using "CARTESIAN_POINT." The data is retrieved and validated using Math3D software before being used to produce ISO 16983 (G-code).



(a)



(b)



(c)

Fig. 3. The 3D CAD model using SolidWorks 2022 for rectangular island (a) Sample 1 (size 0.06m x 0.06m x 0.01m) (b) Sample 2 (size 0.04m x 0.04m x 0.01m) and (c) Sample 3 (size 0.02m x 0.02m x 0.01m)

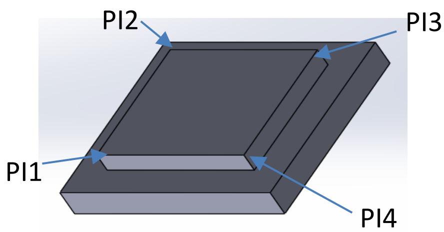
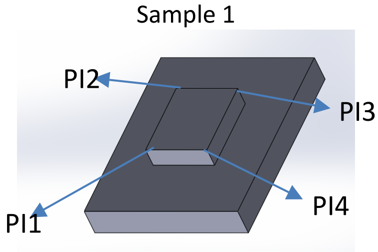
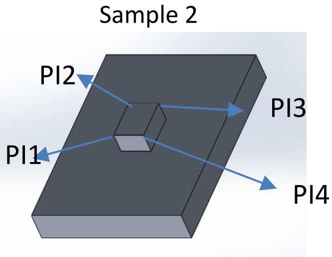
3. Results of Cases Study

The Boundary Representation (B-rep) data structure technique is essential for determining the island profile. This comprehensive framework includes a wide range of 3D data, including edges, vertices, faces, shells, solids, compounds, edge triangulation, face triangulation, polylines on triangulation, location space, and orientation space. The platform for analysis for this approach is the GDE algorithm, and B-rep is the result of its work. The GDE algorithm scrutinizes the geometrical and topological characteristics of the object under investigation. It skilfully arranges and combines the copious information generated from each Cartesian point, producing a coherent and structured representation of the object's geometry and spatial properties.

Using EDGE_LOOP to extract constant coordinate dimensions and variable coordinate values within the face, rectangular island features are distinguished. If the Z value is 10 in cartesian point, the block will be cut. changes that occur in the Z-axis value indicate height or depth. On the other hand, the different X-axis and Y-axis values in the outer boundary of the plane indicate the length and width of the island. In the island sample, it can be identified by an imaginary cut that starts at the origin on the X-axis and Y-axis. Table 2 listed the Recognition Table of Island. These are the minimum and maximum allowable values for all samples, respectively. As can be seen from the table, different sizes would result in different X-axis, Y-axis values, and Z-axis values. These limits ensure that elements within the rectangular island adhere to precise spatial boundaries, which is critical for design accuracy. The comparison of the STEP AP242 File for all samples is listed in Table 3. An imaginary toolpath movement with a 0.01m end mill cutting tool is applied to the block to validate the results, as shown in Table 4.

Based on Table 2, the elements representing point line 1, point line 2, point line 3, and point line 4 shows a representative of each corner of the workpiece that has been cut while island point 1, island point 2, island point 3, and island point 4 represent each rectangle boss corner. All these points have been identified in STEP file AP242 via CARTESIAN_POINT. In addition, all the samples for the rectangle boss show that the maximum and minimum values for X, Y, and Z for point line 1, point line 2, point line 3, and point line 4 are the same. This is due to the same size of workpiece used in this study. For island point 1, island point 2, island point 3, and island point 4 all samples, the maximum and minimum values of X, Y, and Z are different depending on the size of the rectangle boss that has been set.

Table 2
Recognition Table of Island

Samples	Element Name	Lower limit (m)			Upper limit (m)		
		X	Y	Z	X	Y	Z
	Point Line 1 (PL1)	0	0	-0.024	0	0	-0.01
	Point Line 2 (PL2)	0.1	0	-0.024	0.1	0	-0.01
	Point Line 3 (PL3)	0.1	0.1	-0.024	0.1	0.1	-0.01
	Point Line 4 (PL4)	0	0.1	-0.024	0	0.1	-0.01
	Point Island 1 (PI1)	0.015	0.015	-0.01	0.015	0.015	0
	Point Island 2 (PI2)	0.085	0.015	-0.01	0.085	0.015	0
	Point Island 3 (PI3)	0.085	0.085	-0.01	0.085	0.085	0
Sample 1	Point Island 4 (PI4)	0.015	0.085	-0.01	0.015	0.085	0
	Point Line 1 (PL1)	0	0	-0.024	0	0	-0.01
	Point Line 2 (PL2)	0.1	0	-0.024	0.1	0	-0.01
	Point Line 3 (PL3)	0.1	0.1	-0.024	0.1	0.1	-0.01
	Point Line 4 (PL4)	0	0.1	-0.024	0	0.1	-0.01
	Point Island 1 (PI1)	0.03	0.03	-0.01	0.03	0.03	0
	Point Island 2 (PI2)	0.07	0.03	-0.01	0.07	0.03	0
	Point Island 3 (PI3)	0.07	0.07	-0.01	0.07	0.07	0
Sample 2	Point Island 4 (PI4)	0.03	0.07	-0.01	0.03	0.07	0
	Point Line 1 (PL1)	0	0	-0.024	0	0	-0.01
	Point Line 2 (PL2)	0.1	0	-0.024	0.1	0	-0.01
	Point Line 3 (PL3)	0.1	0.1	-0.024	0.1	0.1	-0.01
	Point Line 4 (PL4)	0	0.1	-0.024	0	0.1	-0.01
	Point Island 1 (PI1)	0.04	0.04	-0.01	0.04	0.04	0
	Point Island 2 (PI2)	0.06	0.04	-0.01	0.06	0.04	0
	Point Island 3 (PI3)	0.06	0.06	-0.01	0.06	0.06	0
Sample 3	Point Island 4 (PI4)	0.04	0.06	-0.01	0.04	0.06	0

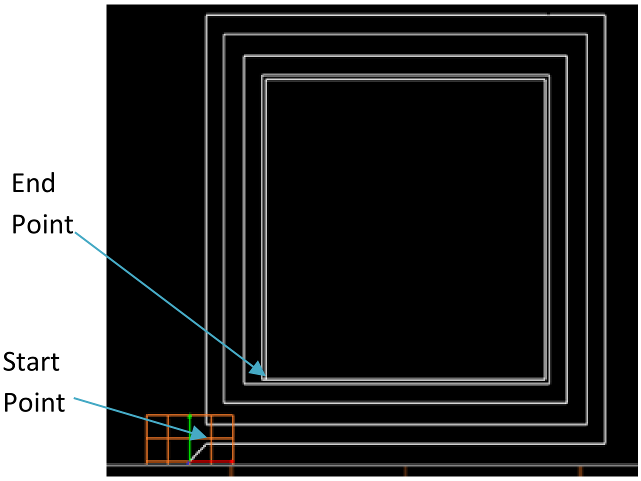
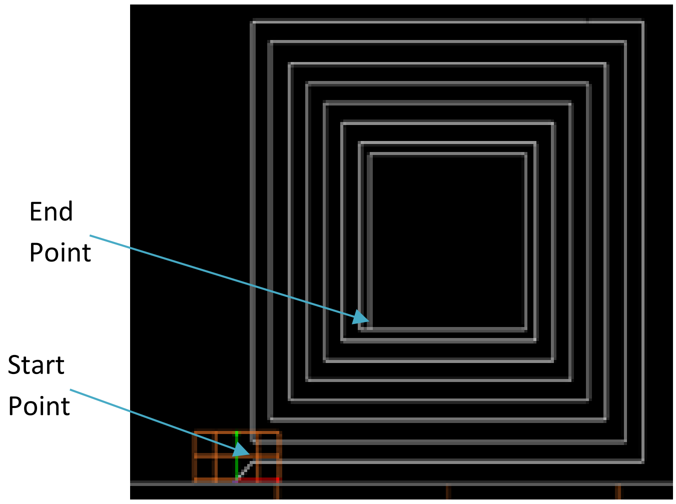
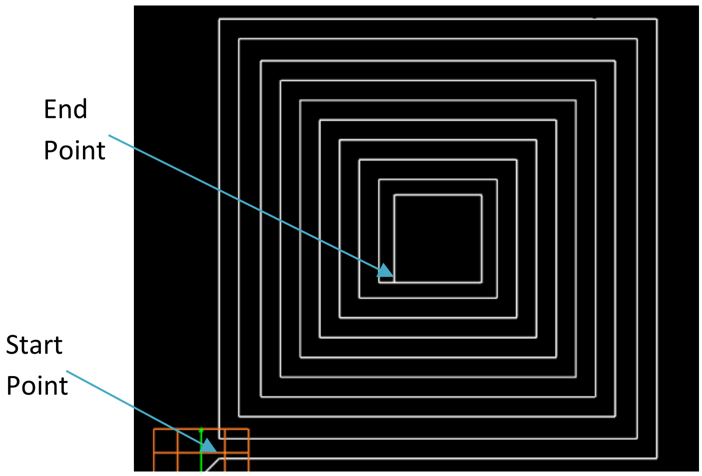
As can be seen in Table 3, there is no difference for all samples in terms of the reference number line, change in header, and amount of ADVANCE_FACE. However, for CLOSED_SHELL, the reference number changes involved for sample 1 are #97, #190, #227, #251, #275, and #292. Sample 2, #162, #208, #239, #263, and #287 show the reference number changes involved while sample 3 #137, #168, #199, #230, #252, #269, #281, and #298 has also been recorded. For sample 1 and sample 2, there is the same reference number line which is #128, #150, and #304. samples 2 and 3 show the same line reference number which is #106 only. For all samples, two other reference numbers are the same which are #66 and #316. This second reference number line is the beginning and end of the reference number line found in the STEP P242 file. In this sample, the header change does not occur and the amount of ADVANCE_FACE for all samples is the same. Moreover, there is a change in the reference number line that occurs on CLOSED_SHELL for each sample. This change is due to one of the main factors being the different size of the workpiece in each sample. In addition, the different size of the workpiece also causes the time factor to cut the workpiece to be different even if using the same tool size diameter.

Table 3
The comparison of STEP AP242 File for all samples

Samples	Reference Number Line (Final Line)	Changes of Header	Total ADVANCE_FACE	CLOSED_SHELL
1	#354	No	11	CLOSED_SHELL ('', (#66, #97, #128, #150, #190, #227, #251, #275, #292, #304, #316)
2	#354	No	11	CLOSED_SHELL ('', (#66, #106, #128, #150, #162, #208, #239, #263, #287, #304, #316)
3	#354	No	11	CLOSED_SHELL ('', (#66, #106, #137, #168, #199, #230, #252, #269, #281, #298, #316)

Table 4 shows all the samples starting from the same starting point until the end point which is different according to the rectangular boss size that has been set. This starting point is the origin point where the value of X is 0, Y is 0 and Z is 0. The image for sample 1 shows the largest rectangular boss size and sample 3 shows the smallest rectangular boss size. This shows that when different rectangular boss sizes are studied, the shape of the tool path for each sample will also be different. For sample 1, the toolpath movement is relatively short, and the time taken to generate the toolpath is very short. Case 2, however, shows a toolpath movement that balances between neither being too long or too short, thus resulting in a moderate time requirement for toolpath generation. In contrast, case 3 features extensive toolpath movement, resulting in a longer time to generate the toolpath. This illustrates that as the size of the square boss decreases, the tool path becomes longer, and the time needed for tool path generation increases.

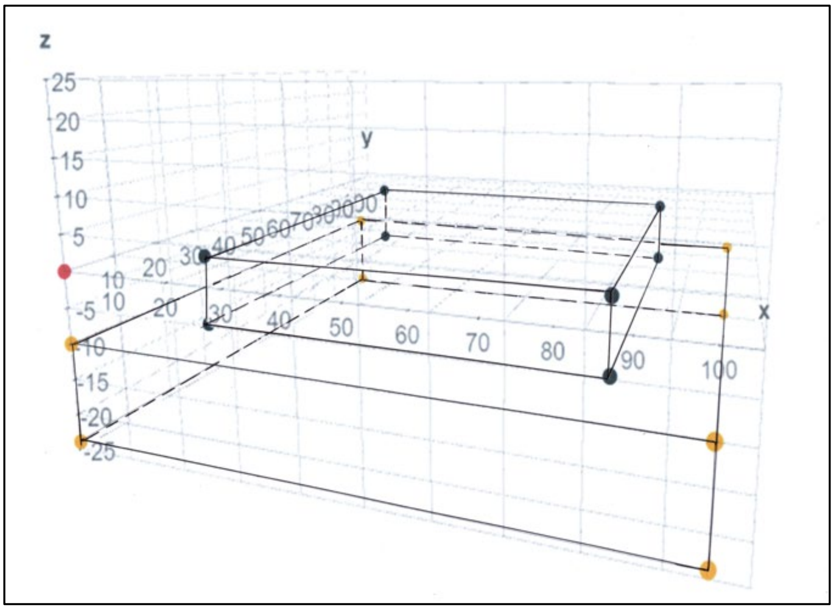
Table 4
An imaginary toolpath movement is applied to the block with a 0.01m end mill cutter based on the STEP data structure

Samples	An imaginary toolpath movement
1	
2	
3	

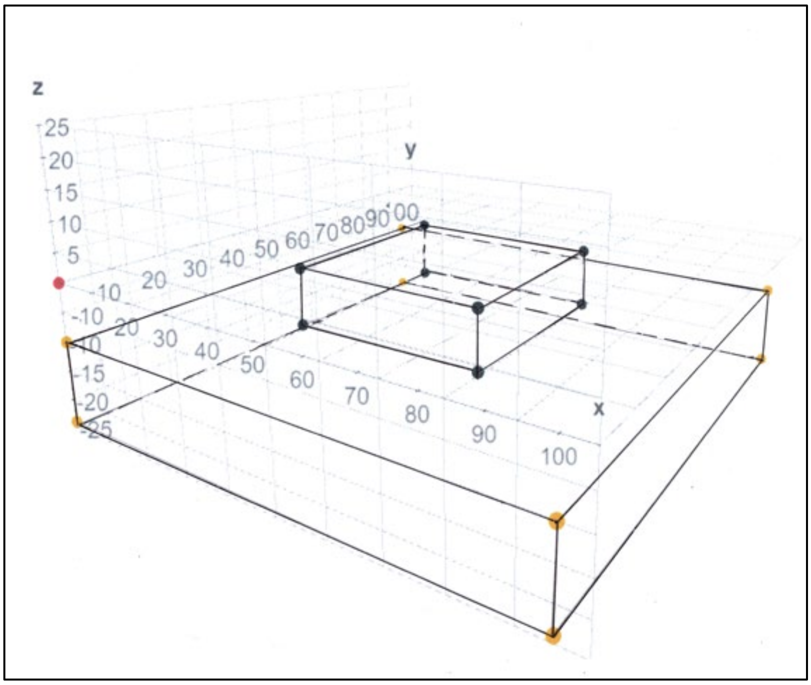
Previous studies used AP203 and AP214 for G code generation, but both types of Application Protocol (AP) contain their respective weaknesses. Additionally, AP203 and AP214 are STL files, according to Yang *et al*., [15], although STL files are widely used in the field of additive manufacturing, however, these STL file does not contain geometrical and surface topology information, making these STL files unsuitable for extracting feature information quickly. These gaps can be overcome by using the STEP AP242 file model used to extract surface features and tolerance information. AP242 is created by covering all the functional scopes of AP203 and AP214. Based on the studies by Mohammed *et al*., [16], Simões *et al*., [17], Mohammed *et al*., [18], Bijnens *et al*., [19], Neb [20], Ding *et al*., [21], Wardhani *et al*., [22], Ramnath *et al*., [23], and Thomas *et al*., [24], they were stated that STEP AP 242 is one of the exchange formats based on Model-Based Design (MBD). It represents a computable format for various types of 3D data, including dimensions, tolerances, mating rules, surface textures, and material specifications. This information is known as PMI (Product Manufacturing Information), where the PMI is directly linked to the 3D CAD model [18].

To validate the accuracy of the data extracted from the STEP AP242 file, the methodology employs Math3D to plot the obtained Cartesian points, coinciding with the manual creation of the 3D island model. Figure 4 visually presents the plotted Cartesian points, showcasing all recognized features from the STEP file. Block edges are highlighted in yellow, island lines are black, and the origin point is red. This visual representation directly verifies the reliability and accuracy of the extracted information by comparing the manually drawn 3D model with Math3D-generated Cartesian points. This crucial validation ensures the precision of the geometric data retrieved from the STEP file, enhancing confidence in the subsequent steps of the toolpath generation methodology.

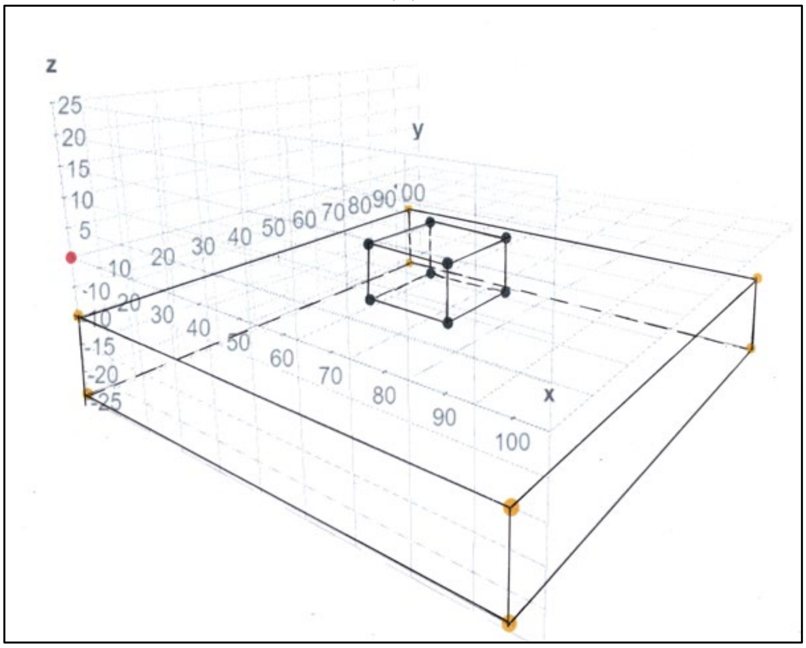
Moreover, this validation process confirms the accuracy of the data extracted and underscores the suitability of the STEP AP242 format in capturing intricate geometric information with precision. The precise alignment of plot points with the intended design emphasizes the file's reliability, especially in CAD/CAM applications where accuracy is crucial. In practical terms, the research findings bolster confidence in the data extraction process, directly impacting subsequent CNC machining operations. Accurately representing geometric features ensures that toolpaths generated from this data contribute to an error-free and precise manufacturing process. In conclusion, the study affirms the robustness of the STEP AP242 standard, highlighting its pivotal role in facilitating accurate geometric data exchange within the engineering and manufacturing sectors.



(a)



(b)



(c)

Fig. 4. The Cartesian point plotted in Math3D after recognizing all the features found in the STEP File for (a) Sample 1 (b) Sample 2 and (c) Sample 3

4. Conclusions

In summary, this research addressed a gap in the existing literature by developing a methodology for identifying and isolating island features in CNC machining using the STEP AP242 file format. The study successfully achieved its objectives, demonstrating the efficient generation of optimized toolpaths through integrating geometric data extraction (GDE) techniques. By creating 3D CAD models and leveraging the standardized STEP format, the research ensured an accurate representation of geometric dimensions and tolerances. Manual drawing and Math3D analysis of different-sized island profile samples verified the methodology's accuracy. Overall, the study's outcomes highlight significant advancements in CNC machining capabilities, showcasing a streamlined toolpath generation process that improves manufacturing efficiency and quality. STEP AP242 and the GDE approach represent a valuable contribution to addressing the challenges associated with island features in CNC machining.

Acknowledgement
This research was not funded by any grant.

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